Measurements of the CKM Angle γ in Tree-Dominated *B* Decays at LHCb

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on behalf of the LHCb Collaboration

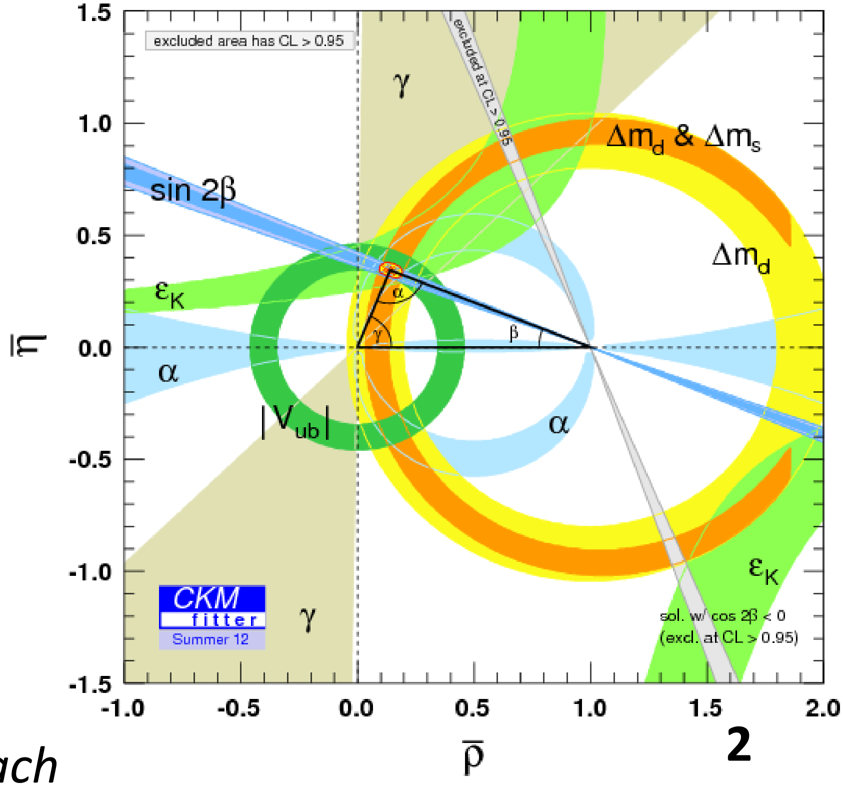
Discrete 2012, Lisbon

γ in Tree-Level *B* Decays

- γ is the least well-constrained angle of the CKM triangle:

  γ = 66±12° *(CKMFitter)*, γ = 76±10° *(UTFit)*

- Measurements of γ from *B* decays mediated only by tree-level transitions provide an "standard candle" for the SM.
- This can be compared with γ values from *B* decays involving loop-level transitions
  - For example $B^0_{(s)} \to hh'$ decays(*)
- Significant difference between these would indicate New Physics contribution to the loop process.



(*) See talk of D. Derkach

Menu of Results

- Time-independent measurements:
  - $B^+ \to D^0 K^+$ with $D^0 \to K\pi$, KK, $\pi\pi$ (Phys. Lett. **B 712** (2012) 203)
  - $B^+ \to D^0 K^+$ with $D^0 \to K\pi\pi\pi$ (LHCb-CONF-2012-030)
  - $B^+ \to D^0 K^+$ with $D^0 \to K_S\pi\pi$, $K_S KK$ (Phys. Lett. **B 718** (2012) 43)
- Gamma combination from time-independent:
  - Using $B^+ \to D^0 K^+$ and $B^+ \to D^0 \pi^+$ (LHCb-CONF-2012-032)
- Time-independent with neutral B decays:
  - $B^0 \to D^0 K^{*0}$ with $D^0 \to KK$ (LHCb-CONF-2012-024)
- Time-dependent measurements:
  - $B_s \to D_s K$ decays (first!) (LHCb-CONF-2012-029)

All using 1.0/fb of 2011 data ($\sqrt{s}$ = 7TeV)

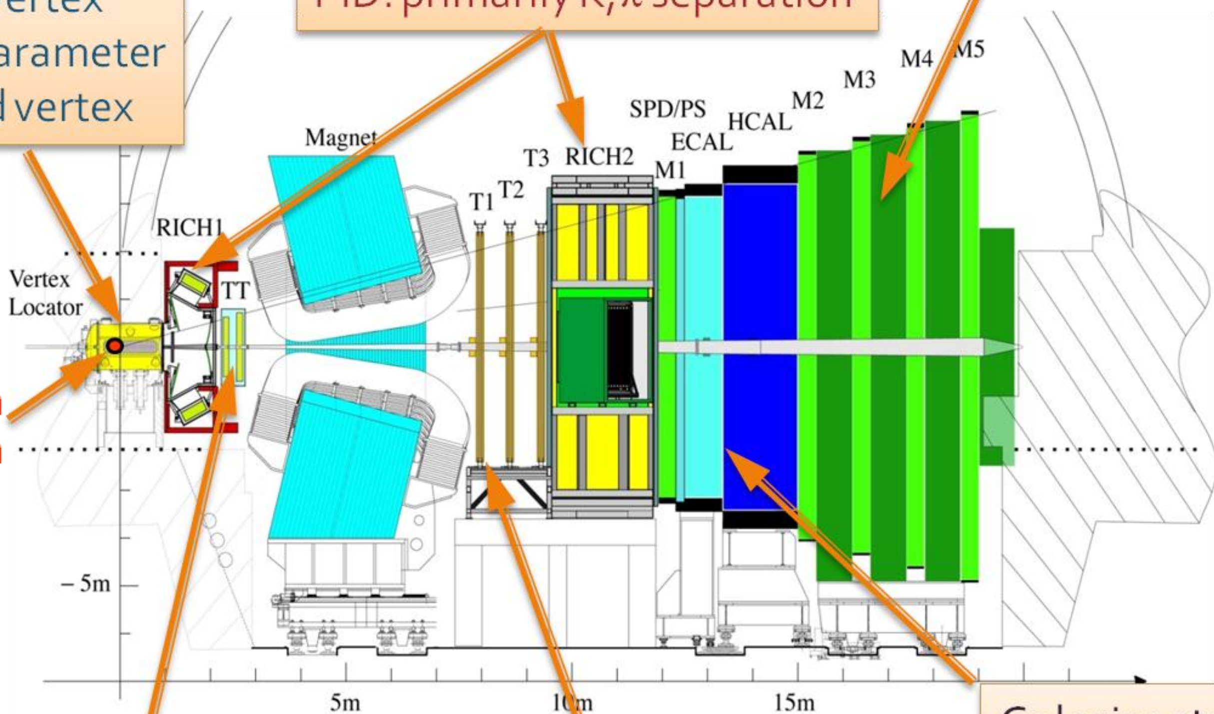
The LHCb Experiment

- Situated on LHC ring; *pp* collisions at E_{CM} = 7 TeV. (8 TeV in 2012)
- Forward arm spectrometer, optimised for study of *B* and *D* decays.

VELO:
primary vertex
impact parameter
displaced vertex

RICH:
PID: primarily K,π separation

Muon System



Interaction region

Hardware trigger reduces event rate to 1MHz, followed by software trigger reducing to several kHz. This allows high trigger efficiency, even on purely hadronic final states.

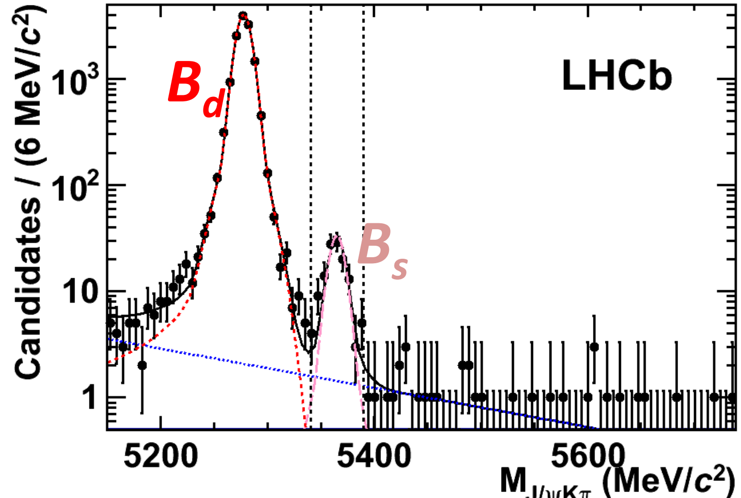
Tracking Station: p for lower energy tracks and long lived V° reconstruction

Tracking Stations:
p of charged particles that traverse the magnet

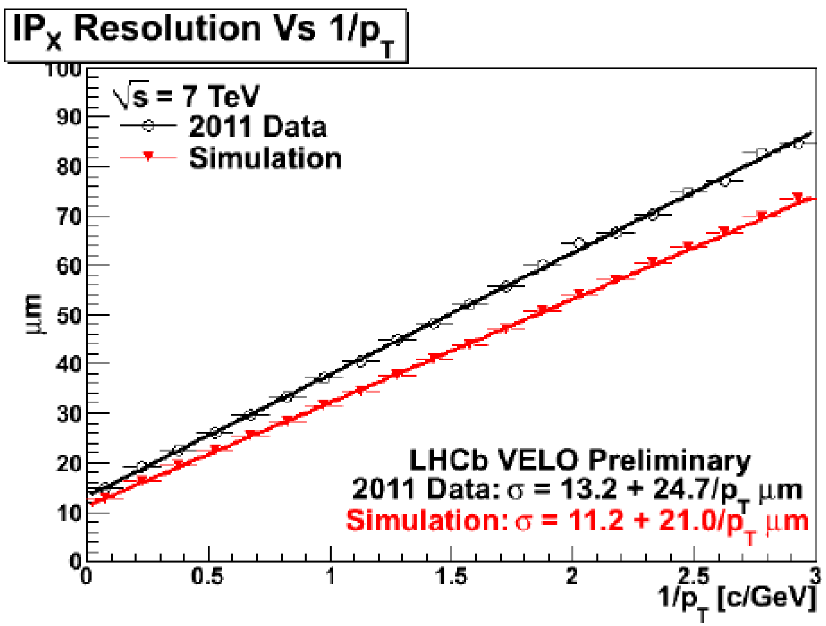
Calorimeters:
PID: h,e,γ, π^{0}

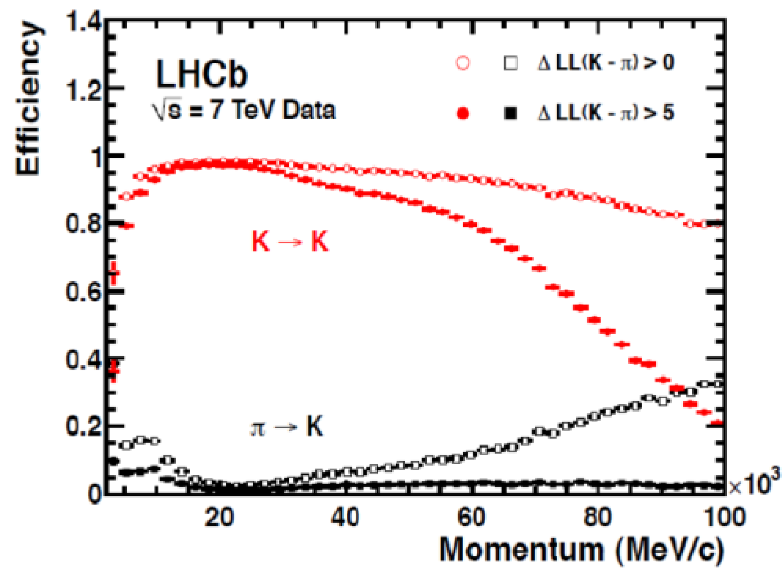
Experimental Aspects

- Impact parameter (IP) and momentum resolution of tracking system allows to separate *B* decay products from prompt tracks, and gives narrow mass resolution
- Hadronic particle identification (from RICH) separates suppressed *DK* modes from favoured $D\pi$ modes



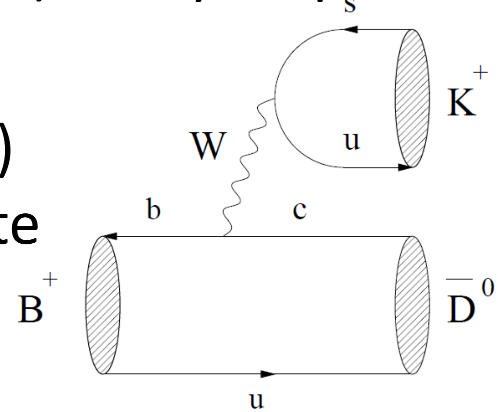
e.g. Branching fraction measurement of $B_s \to J/\psi K^{*0}$ (Phys. Rev. **D 86** (2012) 071102)

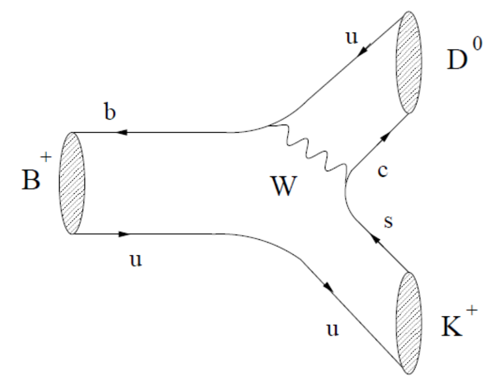




Time-Integrated Methods

- Sensitivity to γ from interference between $b \rightarrow c$ and $b \rightarrow u$ transitions at tree level, when D final state is accessible to both D^0 and $\overline{D}^0$
- Aside from γ, have hadronic unknowns $r_{B(D)}$, $\delta_{B(D)}$, where ratio of favoured to suppressed $B(D)$ decay amplitudes is $r_B\, e^{i(\delta_B - \gamma)}$ $(r_D\, e^{i\delta_D})$
- Method to extract these hadronic unknowns (and γ) depends on the D final state





- Discussed today:
- ***GLW***: $D \rightarrow$ CP-eigenstate, e.g. $\pi\pi$, KK (Phys. Lett. **B 253** (1991) 483, Phys. Lett. **B 265** (1991) 172)
- ***ADS***: $D \rightarrow$ quasi-flavour-specific state, e.g. $K\pi$, $K\pi\pi\pi$ (Phys. Rev. Lett. **78** (1997) 257, Phys. Rev. **D 63** (2001) 036005)
- ***GGSZ***: $D \rightarrow$ self-conjugate 3-body final state, e.g. $K_S\pi\pi$, K_SKK (Phys. Rev. **D 68** (2003) 054018, Phys. Rev. **D 70** (2004) 072003)

GLW, ADS Observables

- The two main GLW observables for $B \to DK$ are the average partial rate R_{CP+} and the asymmetry A_{CP+}, where the CP+ state can be KK or $\pi\pi$:

$$R_{CP+} \equiv 2\frac{\Gamma(B^- \to D_{CP+}K^-) + \Gamma(B^+ \to D_{CP+}K^+)}{\Gamma(B^- \to D^0 K^-) + \Gamma(B^+ \to \bar{D}^0 K^+)} = 1 + {r_B}^2 + 2\kappa r_B \cos\delta_B \cos\gamma$$

$$A_{CP+} \equiv \frac{\Gamma(B^- \to D_{CP+}K^-) - \Gamma(B^+ \to D_{CP+}K^+)}{\Gamma(B^- \to D_{CP+}K^-) + \Gamma(B^+ \to D_{CP+}K^+)} = \frac{2\kappa r_B \sin\delta_B \sin\gamma}{R_{CP+}}$$

- The equivalents also exist for $B \to D\pi$, but the asymmetry is expected to be negligible.
- The main ADS observables for $B \to DK$ relate to the Doubly-Cabibbo-suppressed D final state:

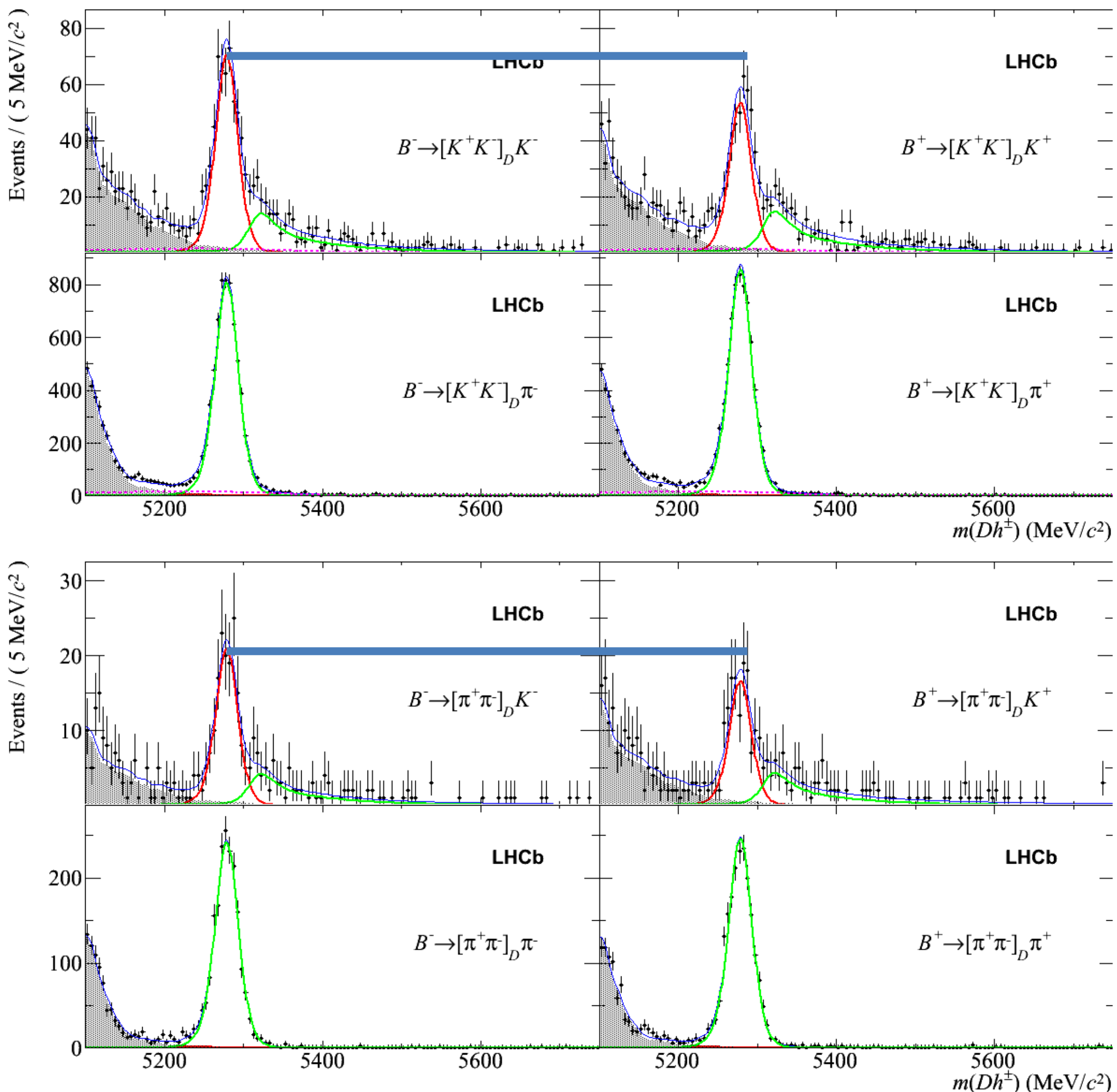
$$\begin{aligned} R_{ADS} &= \frac{\Gamma(B^- \to (K^+\pi^-)_D K^-) + \Gamma(B^+ \to (K^-\pi^+)_D K^+)}{\Gamma(B^- \to (K^-\pi^+)_D K^-) + \Gamma(B^+ \to (K^+\pi^-)_D K^+)} \\ &= r_B^2 + r_D^2 + 2r_D r_B C_f \cos\gamma\cos(\delta_B + \delta_D) \end{aligned}$$

$$\begin{aligned} A_{ADS} &= \frac{\Gamma(B^- \to (K^+\pi^-)_D K^- - \Gamma(B^+ \to (K^-\pi^+)_D K^+)}{\Gamma(B^- \to (K^+\pi^-)_D K^- + \Gamma(B^+ \to (K^-\pi^+)_D K^+)} \\ &= \frac{2r_D r_B C_f \sin\gamma\sin(\delta_B + \delta_D)}{R_{ADS}} \end{aligned}$$

N.B. C_f (or κ) is the coherence factor, with C_f =1 for two-body decay, and 0< C_f<1 for multi-body decay

GLW Results for $B \to DK$

- Raw asymmetries are visible in the suppressed *DK* modes.



After correcting for (small) detector and production asymmetries, obtain:

$$A_K^{KK} = 0.148 \pm 0.037 \pm 0.010,$$

$$A_K^{\pi\pi} = 0.135 \pm 0.066 \pm 0.010,$$

with average: **4.5σ**

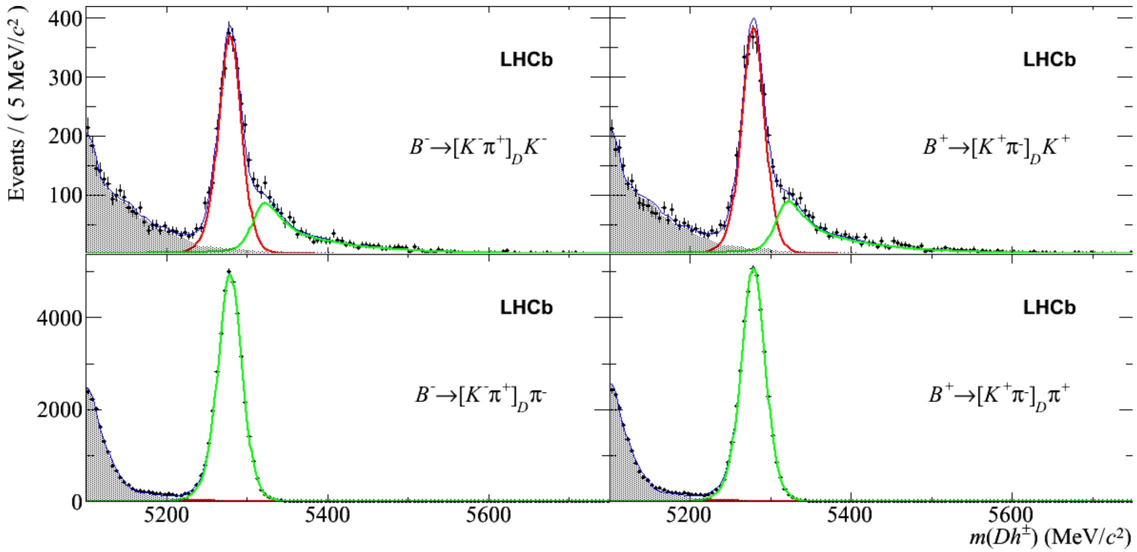
$$\boxed{A_{CP+} = 0.145 \pm 0.032 \pm 0.010}$$

Also:

$$R_{CP+} = 1.007 \pm 0.038 \pm 0.012$$

ADS Results for $B \to DK$

- Raw asymmetries visible in the suppressed D mode (both $D\pi$ and DK)



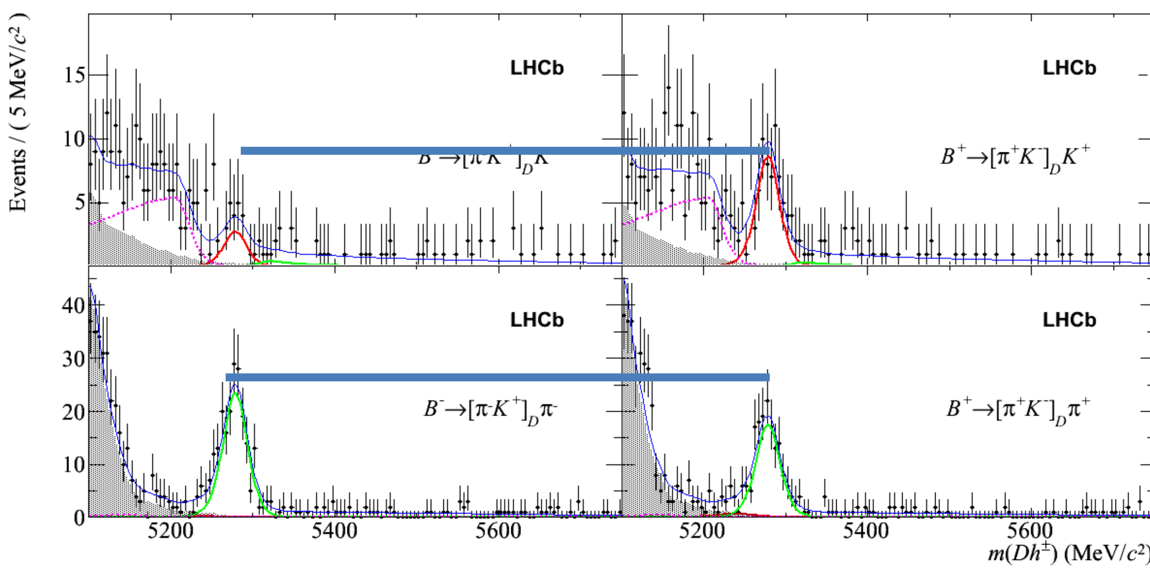
$R_{ADS(\pi)} =$
$0.00410 \pm 0.00025 \pm 0.00005$

$A_{ADS(\pi)} =$ 2.4σ
$0.143 \pm 0.062 \pm 0.011$

10σ
$R_{ADS(K)} =$
$0.0152 \pm 0.0020 \pm 0.0004$

First observation!

$A_{ADS(K)} =$ 4.0σ
$-0.52 \pm 0.15 \pm 0.02$

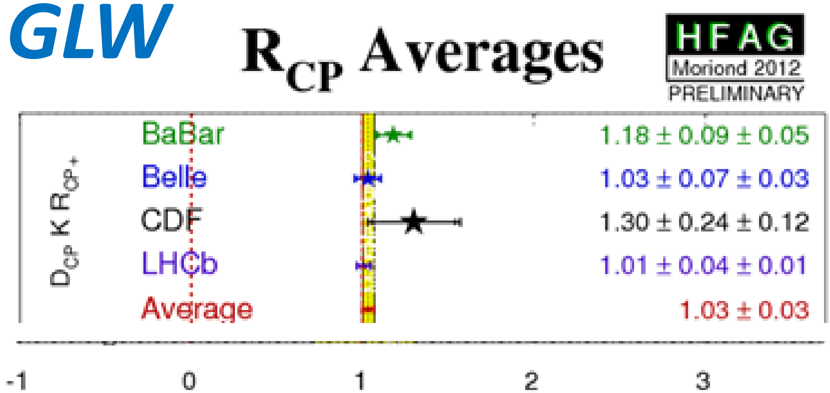


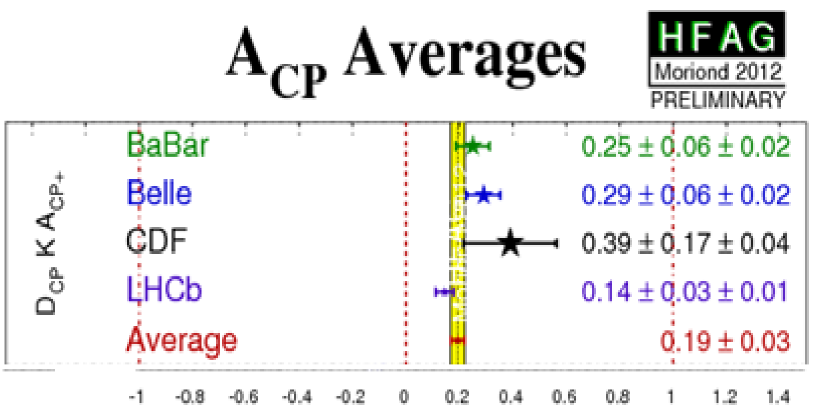
Considering KK, Kπ and $\pi\pi$ together, CPV is observed (5.8σ) in $B \to DK$ decays for the first time .

ADS and GLW Averages

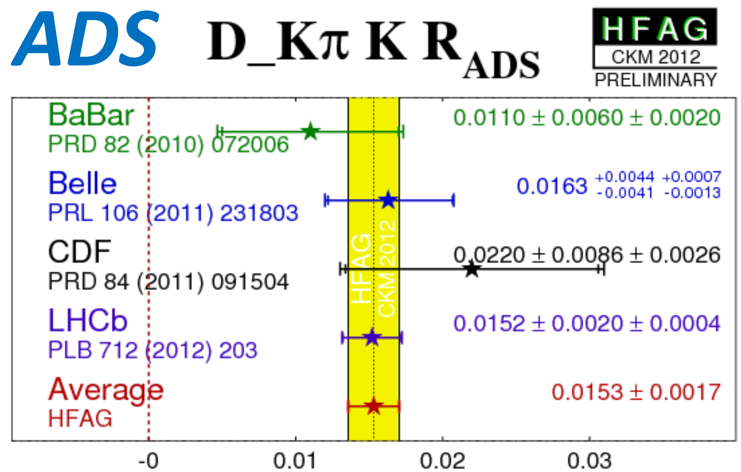
- LHCb results significantly improve on the precision of previous B-Factory and TeVatron measurements.

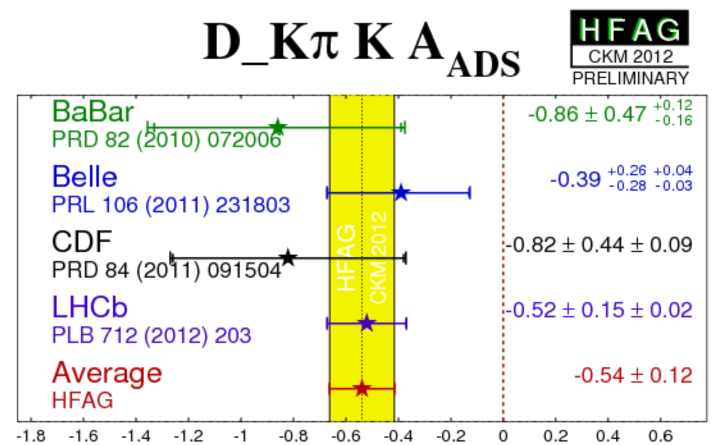
GLW





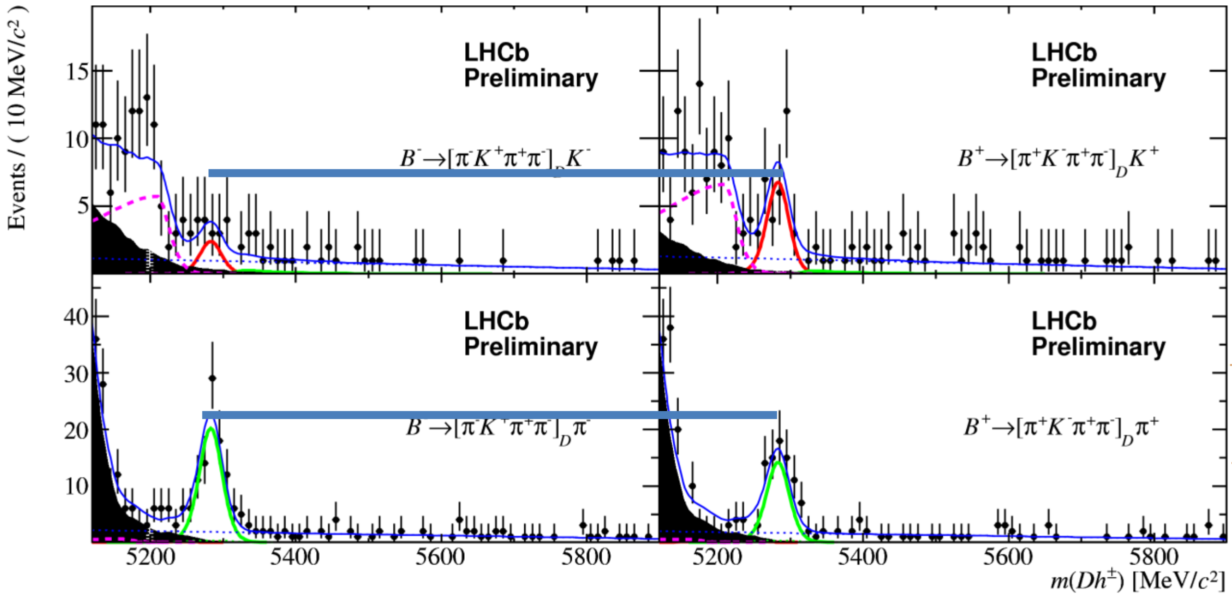
ADS





ADS for $B \to D(K\pi\pi\pi)K$

- Compared to $B \to D(K\pi)K$, r_B and δ_B are unchanged, but the D decay parameters differ.
- So we gain complementary information to $B \to D(K\pi)K$, beyond simply adding further events.



First observations of the 4-body ADS modes in both $B \to D\pi$ (>10σ) and $B \to DK$ (5.1σ):

$$R^{K3\pi}_{\mathrm{ADS}(K)} = 0.0124 \pm 0.0027$$

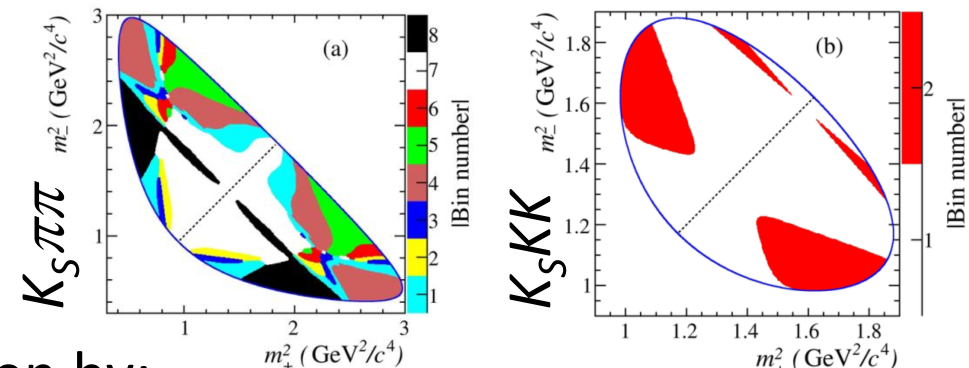
$$R^{K3\pi}_{\mathrm{ADS}(\pi)} = 0.00369 \pm 0.00036$$

Some hint of asymmetry in both $B \to D\pi$ and $B \to DK$:

$$A^{K3\pi}_{\mathrm{ADS}(K)} = -0.42 \pm 0.22 \qquad A^{K3\pi}_{\mathrm{ADS}(\pi)} = +0.13 \pm 0.10$$

GGSZ Analysis of $B \to DK$

- Can measure γ by comparing Dalitz plots of $D \to K_S\pi\pi$ (or K_SKK) decay for $B^+ \to DK^+$ and $B^- \to DK^-$
- Need information on how D decay amplitude varies over Dalitz plot
- Current LHCb analysis uses CLEO-c measurements of the strong phase variation as input (Phys. Rev. **D 82** (2010) 112006)
- Dalitz plots are binned in regions of similar strong phase, numbered from $-n$ to n:



- Number of events in i^{th} bin is given by:

for B^+: $N^+_{\pm i} = h_{B^+}\left[K_{\mp i} + (x_+^2 + y_+^2)K_{\pm i} + 2\sqrt{K_i K_{-i}}(x_+ c_{\pm i} \mp y_+ s_{\pm i})\right]$

for B^-: $N^-_{\pm i} = h_{B^-}\left[K_{\pm i} + (x_-^2 + y_-^2)K_{\mp i} + 2\sqrt{K_i K_{-i}}(x_- c_{\pm i} \pm y_- s_{\pm i})\right]$

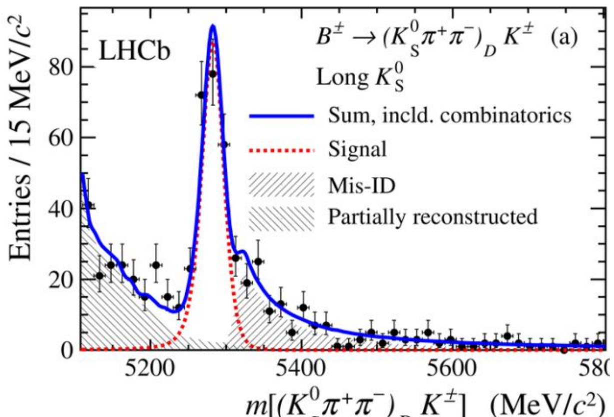
c_i (s_i) is cos(sin) of strong phase diff. in each bin (taken from CLEO-c)

We then measure:
$$\boxed{\begin{aligned} x_\pm &= r_B\cos(\delta_B \pm \gamma) \\ y_\pm &= r_B\sin(\delta_B \pm \gamma) \end{aligned}}$$

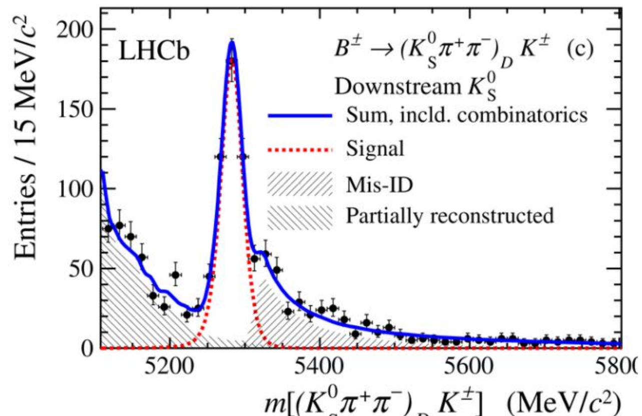
K_i represent (known) Dalitz distribution in flavour-tagged D decays

GGSZ Analysis of $B \to DK$

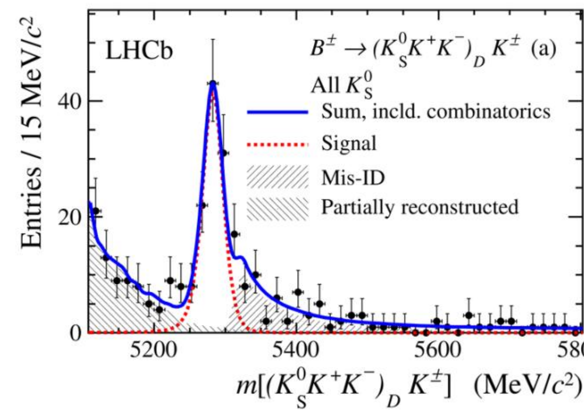
- Events divided according to K_S reconstruction: decays within VeLo ("long K_S") or after leaving VeLo ("downstream K_S").
- Use $B \to D\pi$ as control mode (assume no CPV there)



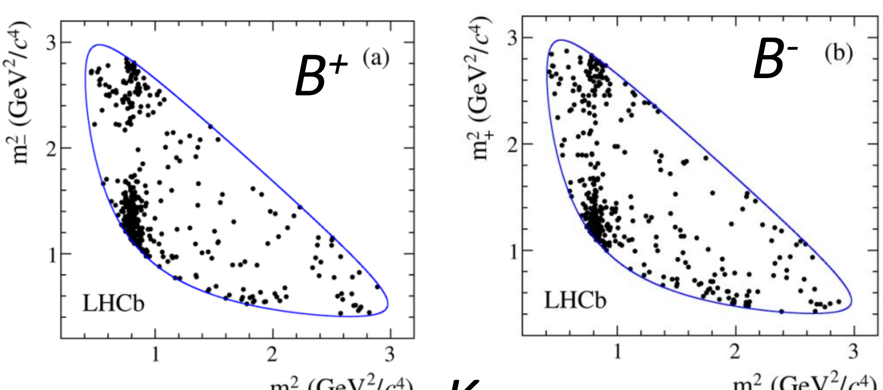
$K_S\pi\pi$, long K_S (N_{sig} = 213±13)



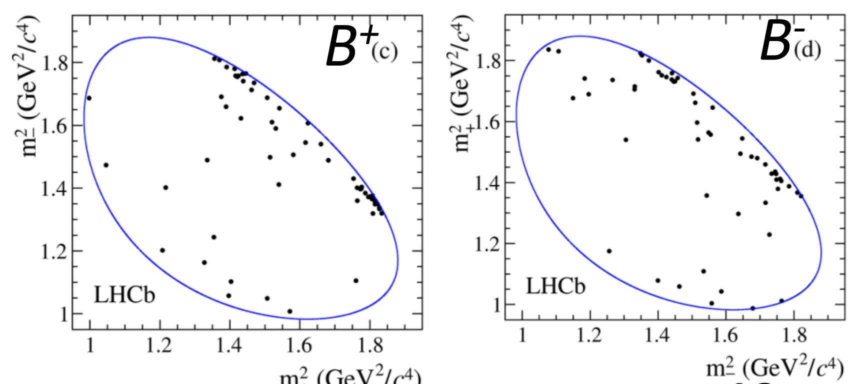
$K_S\pi\pi$, downstream K_S (N_{sig} = 441±25)



K_SKK, all K_S (N_{sig} = 102±5)



$K_S\pi\pi$



K_SKK

GGSZ Results

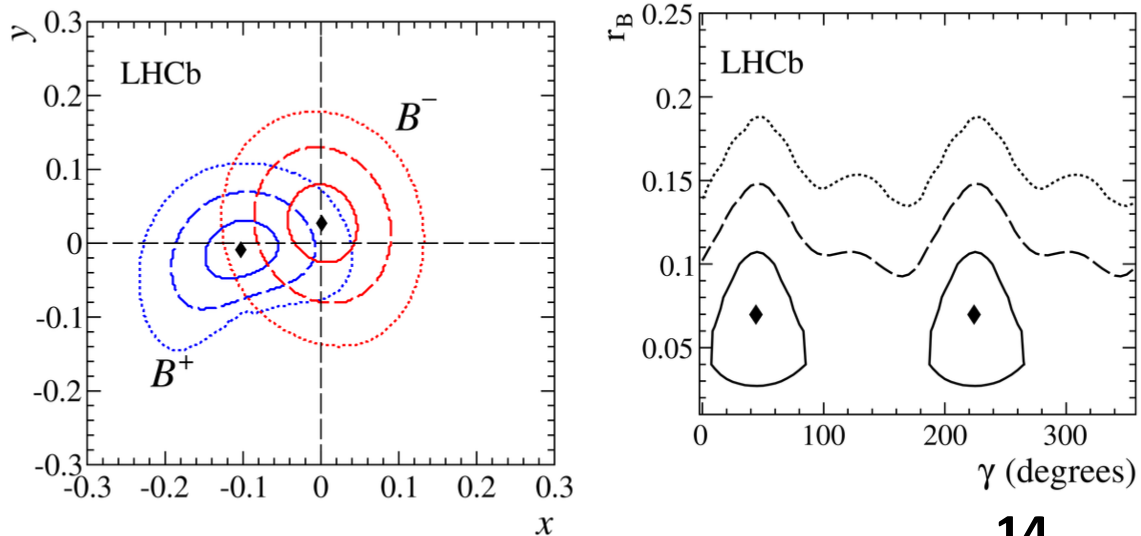
- Dominant experimental systematic is assumption of no CPV in $B \to D\pi$ (used to determine efficiencies).
- Third uncertainty is that from the CLEO-c inputs.

$$x_- = (0.0 \pm 4.3 \pm 1.5 \pm 0.6) \times 10^{-2}, \quad y_- = (2.7 \pm 5.2 \pm 0.8 \pm 2.3) \times 10^{-2}$$

$$x_+ = (-10.3 \pm 4.5 \pm 1.8 \pm 1.4) \times 10^{-2}, \quad y_+ = (-0.9 \pm 3.7 \pm 0.8 \pm 3.0) \times 10^{-2}$$

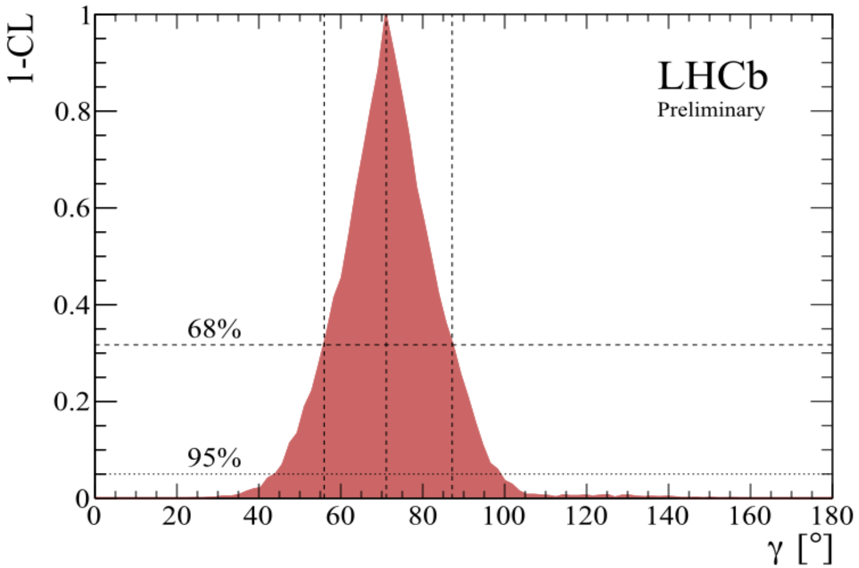
- From these, extract: $\boxed{r_B = 0.07 \pm 0.04,\ \gamma = (44^{+43}_{-38})^\circ}$

- Despite the precision on x and y being similar to the B-Factories, the low measured value of r_B hurts the precision on γ.

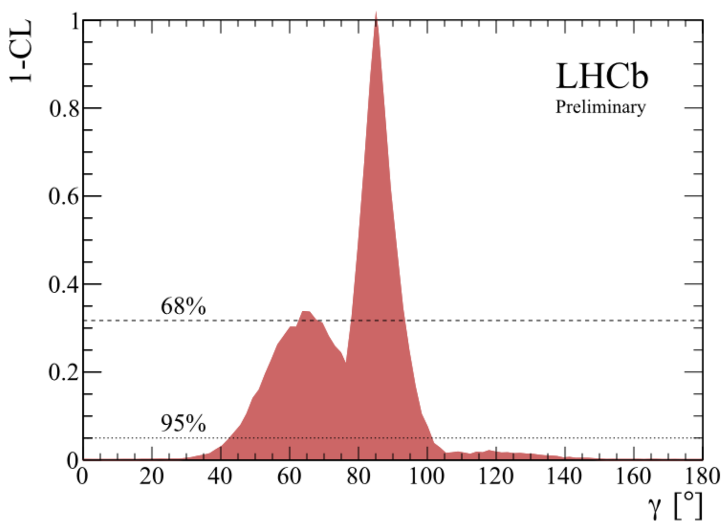


Gamma Combination

- Uses LHCb analyses of $B \to Dh$ with $D \to \{hh, hhhh, K_S hh\}$ ($h = \{K,\pi\}$), plus CLEO data on $D \to K\pi\pi\pi$ strong phase (Phys. Rev. **D 80** (2009) 031105)
- The experimental likelihoods are combined as $\mathcal{L}(\vec{\alpha}) = \prod_i f_i(\vec{A}_i^{\mathrm{obs}} | \vec{A}_i(\vec{\alpha}_i))$, where A are the experimental observables (R_{CP}, x_+, etc) and α are the physics parameters (γ, r_B, etc).
- Confidence intervals are obtained from this in a frequentist way.



$B \to DK$ only: $\boxed{\gamma = (71.1\,^{+16.6}_{-15.7})^\circ}$



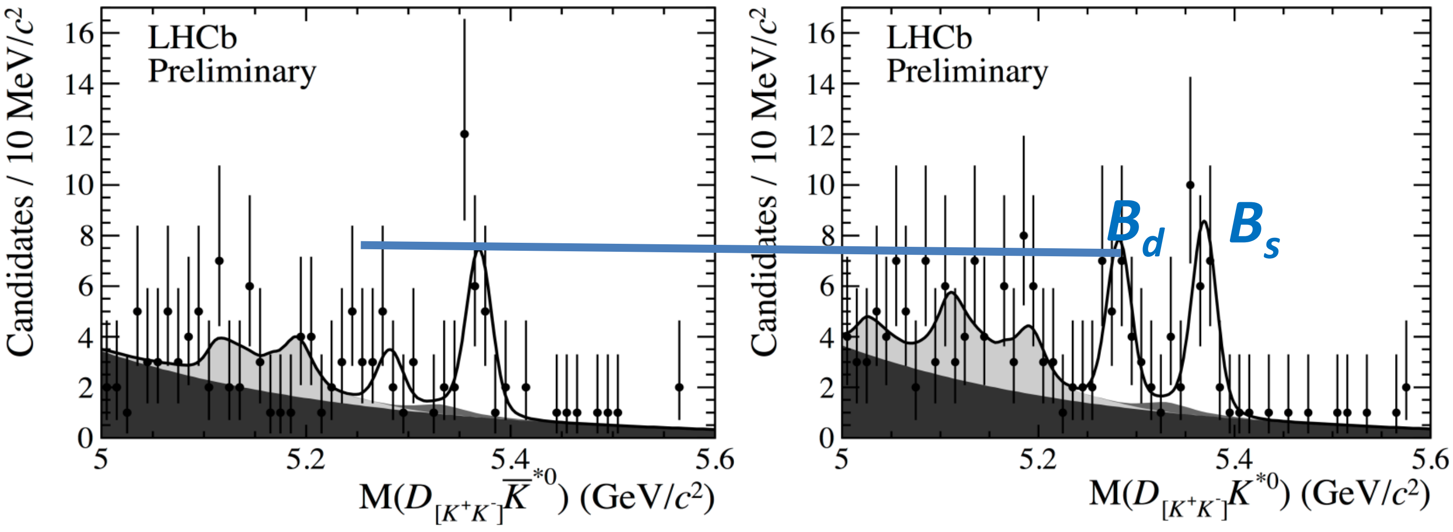
$B \to DK$ and (a first!) $B \to D\pi$:

$\gamma \in [61.8, 67.8]^\circ$ or $[77.9, 92.4]^\circ$ @68% CL ,

$\gamma \in [43.8, 101.5]^\circ$ @95% CL

GLW with $B_d \to D(KK)K^{*0}$

- Similar diagram to internal tree of $B^+ \to DK^+$, but with spectator $u \to d$ quark giving $K^+ \to K^{*0}$ (sign of Kaon from K^{*0} tags flavour of B at decay)
- Both diagrams are colour-suppressed, leading to larger interference but also smaller yields.

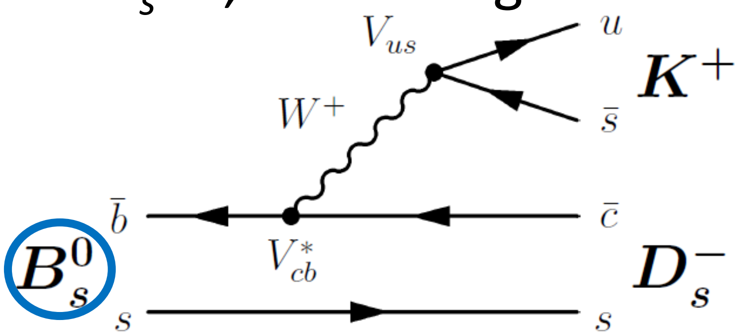


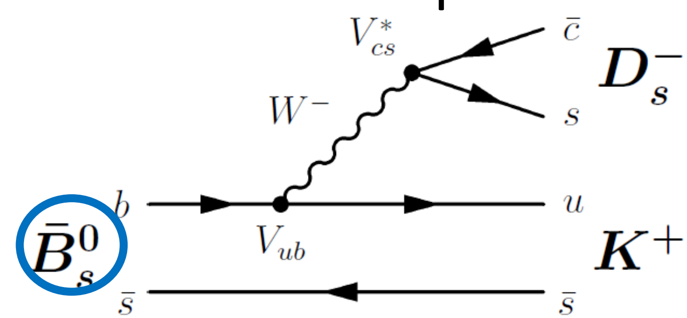
The first observation of $B_d \to D(KK)K^{*0}$ is made, with a significance (summing K^{*0} and $\overline{K}^{*0}$) of 5.1σ

- Hint of asymmetry in $B_d \to D(KK)K^{*0}$: $\boxed{\mathcal{A}_d^{KK} = -0.47\,^{+0.24}_{-0.25}\,(\text{stat}) \pm 0.02\,(\text{syst})}$
- No hint of asymmetry in $B_s \to D(KK)K^{*0}$: $\mathcal{A}_s^{KK} = 0.04 \pm 0.17\,(\text{stat}) \pm 0.01\,(\text{syst})$
- Ratio to favoured $B_d \to D(K\pi)K^{*0}$: $\mathcal{R}_d^{KK} = 1.42^{+0.41}_{-0.35}\,(\text{stat}) \pm 0.07\,(\text{syst})$

Measuring γ with $B_s \to D_s K$

- Tree diagrams of similar magnitude exist for both B_s and $\overline{B}_s$ decaying to $D_s^- K^+$, hence large interference between them is possible.





- Using a flavour-tagged, time-dependent analysis, we can measure four decay rates (B_s or $\overline{B}_s$ to $D_s^+K^-$ or $D_s^-K^+$) and extract γ in an unambiguous and theoretically clean way.

$$\frac{d\Gamma_{B_s^0 \to f}(t)}{dt} = \frac{1}{2}|A_f|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - D_f \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_f \cos(\Delta m_s t) - S_f \sin(\Delta m_s t)\right]$$

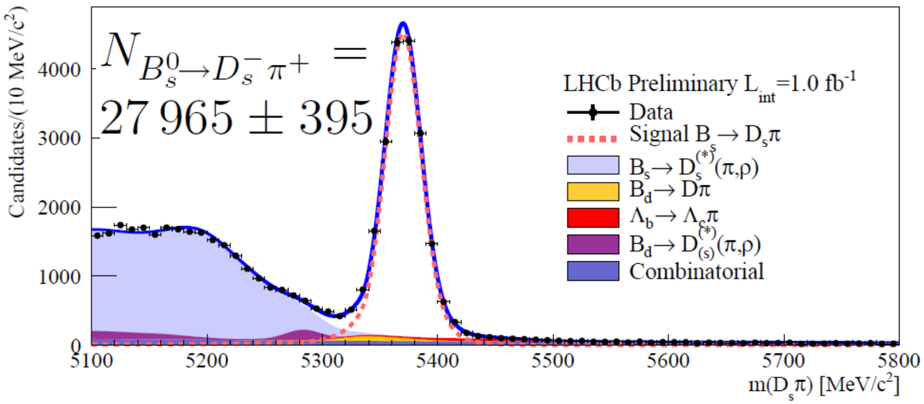
$$\frac{d\Gamma_{\bar{B}_s^0 \to f}(t)}{dt} = \frac{1}{2}|A_f|^2\left|\frac{p}{q}\right|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - D_f \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C_f \cos(\Delta m_s t) + S_f \sin(\Delta m_s t)\right]$$

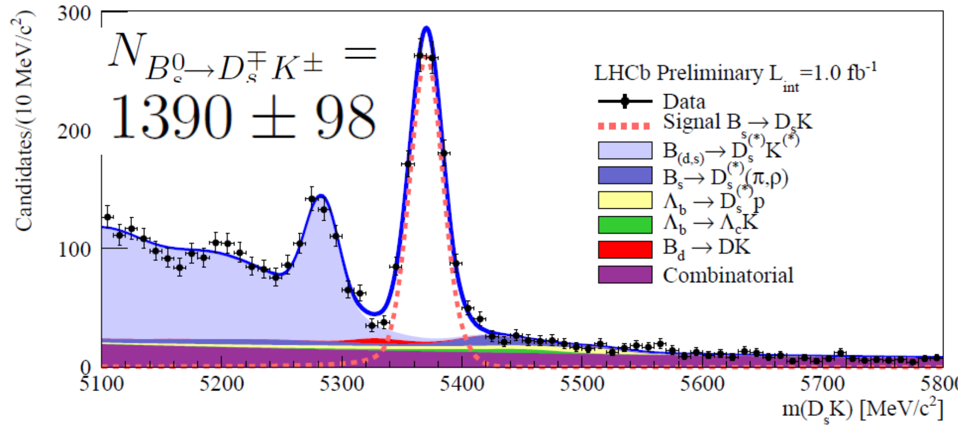
$$C_f = C_{\bar{f}} = C = \frac{1 - r_{D_sK}^2}{1 + r_{D_sK}^2} \qquad D_f = \frac{2r_{D_sK}\cos(\Delta - (\gamma - 2\beta_s))}{1 + r_{D_sK}^2} \qquad S_f = \frac{2r_{D_sK}\sin(\Delta - (\gamma - 2\beta_s))}{1 + r_{D_sK}^2}$$

($r_{D_sK} = |A(\overline{B}_s^0 \to D_s^- K^+)/A(B_s^0 \to D_s^- K^+)|$, Δ is strong phase difference)

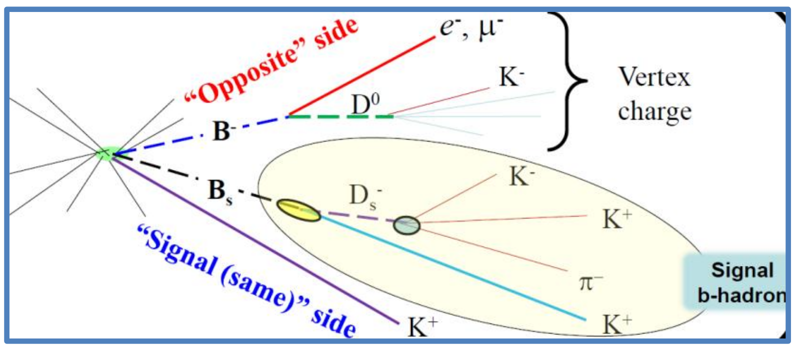
Ingredients for $B_s \to D_s K$

Mass fits (sum of three D_s final states: $KK\pi$, $K\pi\pi$ and $\pi\pi\pi$):



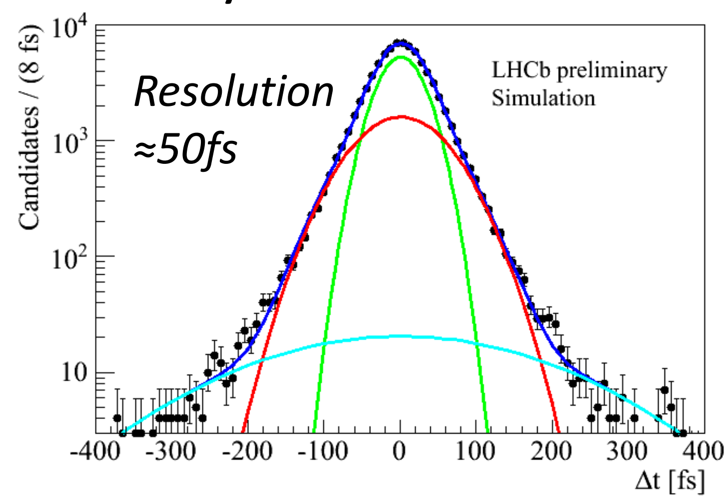


Flavour tagging:



Only Opposite-side (OS) tagging in this analysis, with εD^2 = (1.9±0.3)%. Same-side (SS) tagging to be added in future.

Decay time resolution:



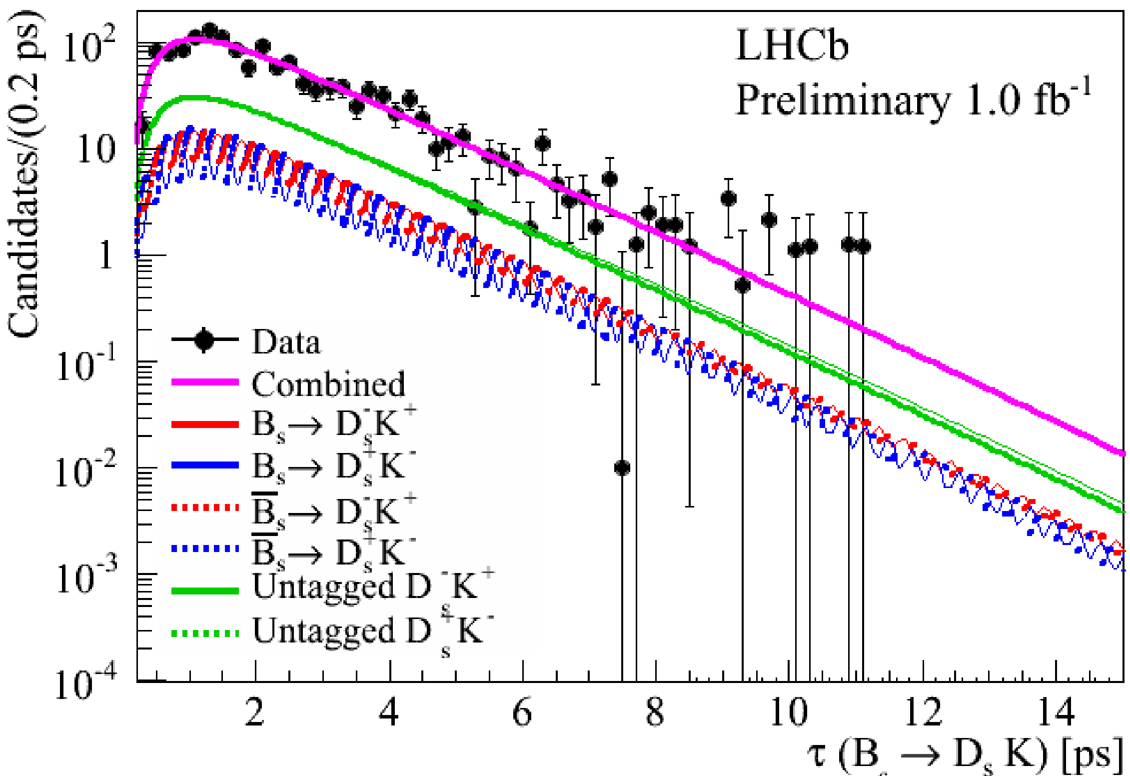
$B_s \to D_s K$ Results

- The CPV parameters in $B_s \to D_s K$ are measured for the first time:

$$C = 1.01 \pm 0.50 \pm 0.23$$

$$S_f = -1.25 \pm 0.56 \pm 0.24 \qquad S_{\bar{f}} = 0.08 \pm 0.68 \pm 0.28$$

$$D_f = -1.33 \pm 0.60 \pm 0.26 \qquad D_{\bar{f}} = -0.81 \pm 0.56 \pm 0.26$$



Dominant systematic uncertainties arise from fixed parameters (Δm_s, Γ_s, $\Delta\Gamma_s$, acceptance) and (for C and S) flavour tagging calibration.

No attempt yet to determine γ (need to understand covariance matrix for systematics).

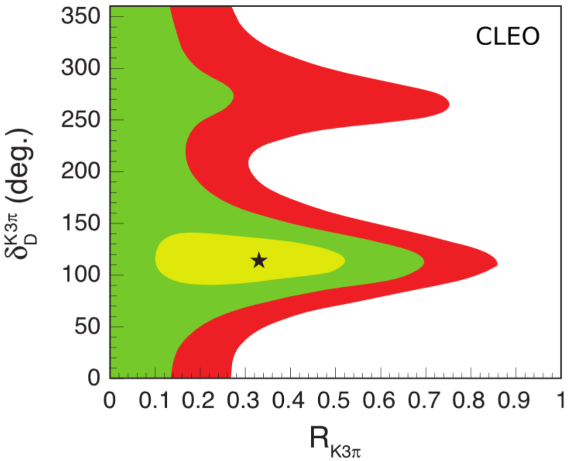
Summary & Prospects

- LHCb has made its first measurements of γ with $B^+ \to D^0 K^+$ and $B^+ \to D^0 \pi^+$ decays, using various methods (ADS, GLW, GGSZ) depending on the D^0 decay mode.
- At the moment, no one method dominates the sensitivity.
- Combination of $B^+ \to D^0 K^+$ results gives $\gamma = (71.1\ ^{+16.6}_{-15.7})^\circ$, which has similar precision to the Belle and Babar results.
- LHCb also has first results on CP parameters in other modes: $B_d \to D^0(KK)K^{*0}$ and $B_s \to D_s K$.
- Work on new channels in the pipeline, e.g. $D_s K\pi\pi$, $D^0 K\pi\pi$.
- Stay tuned for more results in the future!
  - LHCb has already collected ≈2.0/fb at 8 TeV in 2012

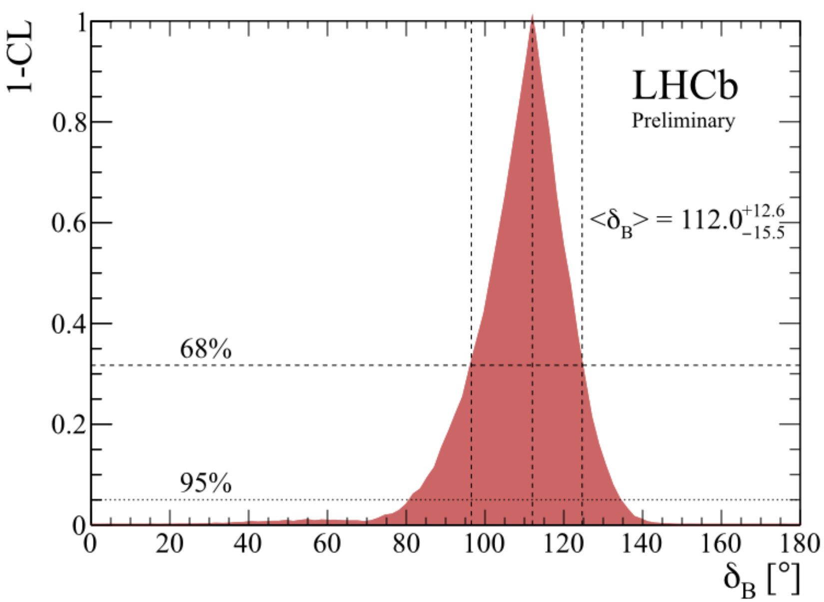
Backup

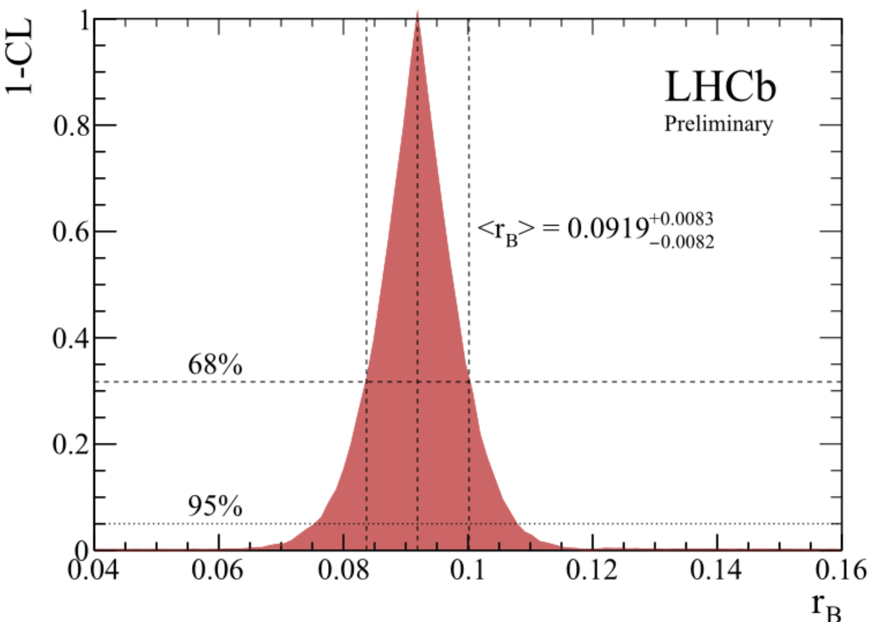
Gamma Combination

- CLEO-c result on $D \rightarrow K\pi\pi\pi$:



- From $B \rightarrow DK$ decays only:

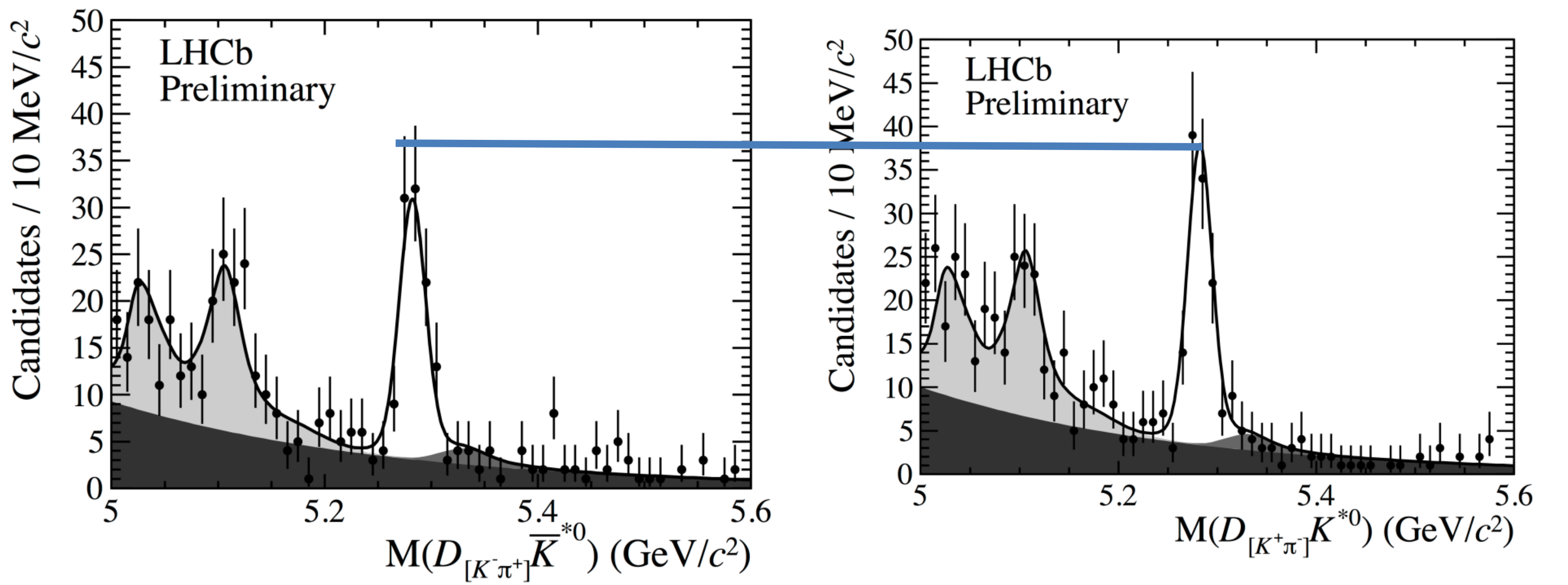




GLW with $B \to D(KK)K^{*0}$

- Check with favoured $B \to D(K\pi)K^{*0}$ mode: no significant asymmetry seen.

$$\mathcal{A}_d^{\text{fav}} = -0.08 \pm 0.08 \text{ (stat)} \pm 0.01 \text{ (syst)}$$



Measuring γ with $B_s \to D_s K$

$$\Gamma_{B_s^0\to f}(t) = |A_f|^2(1+|\lambda_f|^2)\frac{e^{-\Gamma_s t}}{2}\cdot \left(\cosh\frac{\Delta\Gamma_s t}{2} + D_f \sinh\frac{\Delta\Gamma_s t}{2} + C_f\cos\Delta m_s t - S_f \sin\Delta m_s t\right),$$

$$\Gamma_{\bar{B}_s^0\to f}(t) = |A_f|^2\left|\frac{p}{q}\right|^2(1+|\lambda_f|^2)\frac{e^{-\Gamma_s t}}{2}\cdot \left(\cosh\frac{\Delta\Gamma_s t}{2} + D_f \sinh\frac{\Delta\Gamma_s t}{2} - C_f\cos\Delta m_s t + S_f \sin\Delta m_s t\right),$$

$$\Gamma_{B_s^0\to \bar{f}}(t) = |\bar{A}_{\bar{f}}|^2(1+|\bar{\lambda}_{\bar{f}}|^2)\frac{e^{-\Gamma_s t}}{2}\cdot \left(\cosh\frac{\Delta\Gamma_s t}{2} + D_{\bar{f}} \sinh\frac{\Delta\Gamma_s t}{2} + C_{\bar{f}}\cos\Delta m_s t - S_{\bar{f}} \sin\Delta m_s t\right),$$

$$\Gamma_{\bar{B}_s^0\to \bar{f}}(t) = |\bar{A}_{\bar{f}}|^2\left|\frac{q}{p}\right|^2(1+|\bar{\lambda}_{\bar{f}}|^2)\frac{e^{-\Gamma_s t}}{2}\cdot \left(\cosh\frac{\Delta\Gamma_s t}{2} + D_{\bar{f}} \sinh\frac{\Delta\Gamma_s t}{2} - C_{\bar{f}}\cos\Delta m_s t + S_{\bar{f}} \sin\Delta m_s t\right),$$

For D_sK, $|\lambda_f| = |\bar{\lambda}_{\bar{f}}|$, so:

$$C_f = C_{\bar{f}} = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2},$$

$$S_f = \frac{2\mathcal{I}m(\lambda_f)}{1+|\lambda_f|^2}, \quad D_f = \frac{2\mathcal{R}e(\lambda_f)}{1+|\lambda_f|^2},$$

$$S_{\bar{f}} = \frac{2\mathcal{I}m(\bar{\lambda}_{\bar{f}})}{1+|\bar{\lambda}_{\bar{f}}|^2}, \quad D_{\bar{f}} = \frac{2\mathcal{R}e(\bar{\lambda}_{\bar{f}})}{1+|\bar{\lambda}_{\bar{f}}|^2}.$$

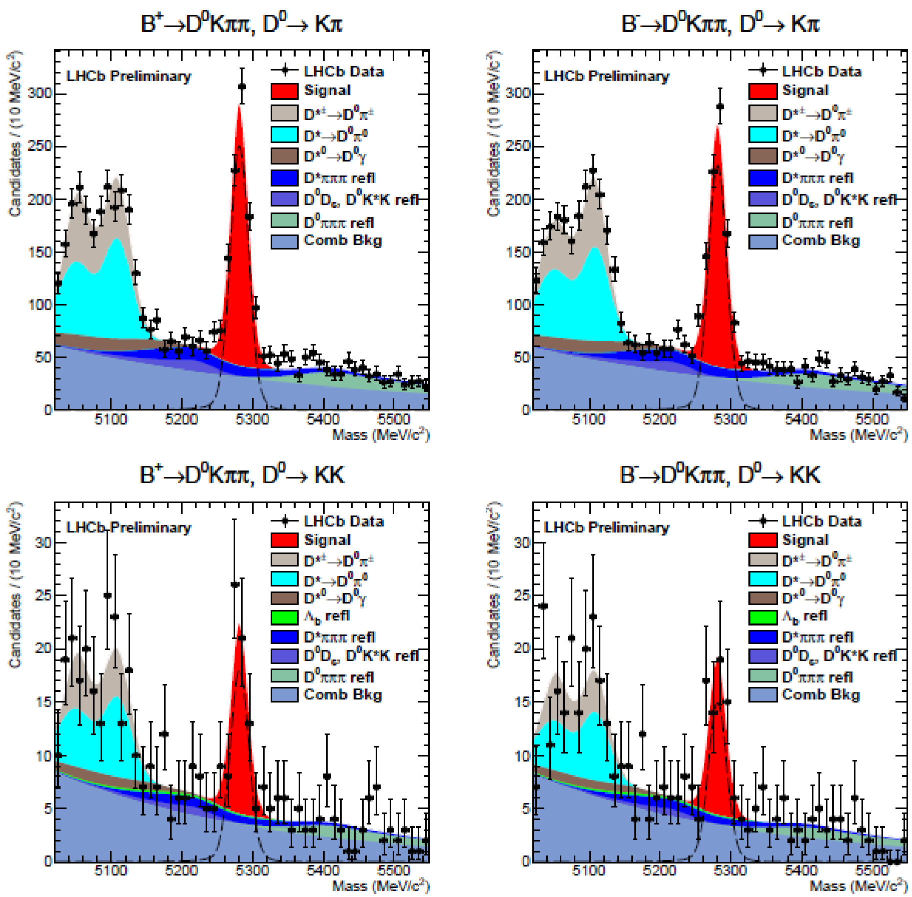
$$C = \frac{1-r_{D_sK}^2}{1+r_{D_sK}^2},$$

$$D_f = \frac{2r_{D_sK}\cos(\Delta - (\gamma - 2\beta_s))}{1+r_{D_sK}^2}, \quad D_{\bar{f}} = \frac{2r_{D_sK}\cos(\Delta + (\gamma - 2\beta_s))}{1+r_{D_sK}^2},$$

$$S_f = \frac{2r_{D_sK}\sin(\Delta - (\gamma - 2\beta_s))}{1+r_{D_sK}^2}, \quad S_{\bar{f}} = \frac{2r_{D_sK}\sin(\Delta + (\gamma - 2\beta_s))}{1+r_{D_sK}^2}.$$

GLW with $B^+ \to D^0 K\pi\pi$

- First observation of $B^+ \to D^0(\to KK)K\pi\pi$, and measurement of CP observables
- With larger dataset, aim to also perform ADS analysis and obtain constraints on γ



$$R_{CP+} = \quad 0.95 \quad \pm 0.11 \quad (\text{stat}) \pm 0.02 \quad (\text{syst})$$
$$A_s^{CP+} = -0.14 \quad \pm 0.10 \quad (\text{stat}) \pm 0.01 \quad (\text{syst})$$

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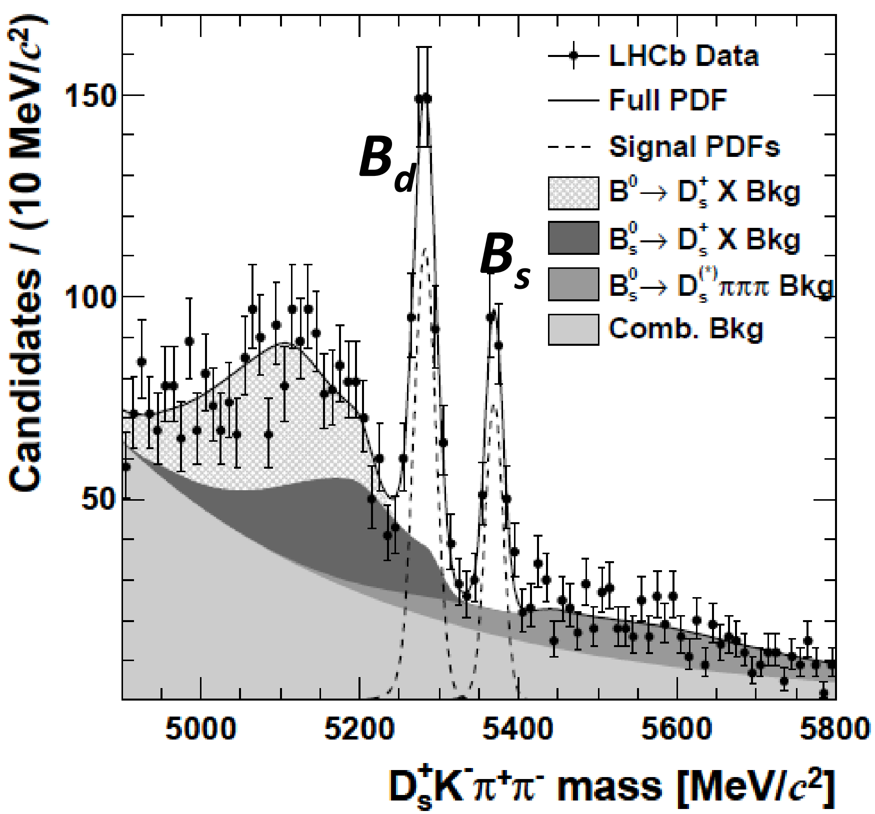
Observation of $B_s \to D_s K \pi\pi$

- Time-dependent analysis can be done in a similar way to $B_s \to D_s K$
- First, need to observe it!
- Using only $\varphi\pi$ and K^*K submodes of $D_s \to KK\pi$, to improve S/B



$$N(B^0) = 402 \pm 33$$
$$N(B_s) = 216 \pm 21$$

$$\frac{\mathcal{B}(\overline{B}{}_s^0 \to D_s^+ K^- \pi^+ \pi^-)}{\mathcal{B}(\overline{B}{}_s^0 \to D_s^+ \pi^- \pi^+ \pi^-)} = (5.2 \pm 0.5 \pm 0.3) \times 10^{-2}$$

$$\frac{\mathcal{B}(\overline{B}{}^0 \to D_s^+ K^- \pi^+ \pi^-)}{\mathcal{B}(\overline{B}{}_s^0 \to D_s^+ K^- \pi^+ \pi^-)} = 0.54 \pm 0.07 \pm 0.07,$$

hep-ex/1211.1541
(submitted to Phys. Rev. ***D****)*